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Parametric study of solid propellant slotted grain

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Parametric study of solid propellant slotted grain

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Abstract. One of the goals in solid rocket motor design is to have as large volumetric loading as possible keeping the basic requirements unaffected. Slotted grain can achieve this goal as it has the advantages of sliver-free and no stress-concentration regions that occur in other internal burning grains as star grain and wagon wheel grain. It has the disadvantage of exposing the motor wall to hot gases. In this paper, the geometry of slotted grain is discussed and the effect of design parameters (e.g., number of slots, dimensions of the slot, etc.) of slotted grain on grain burn back is explained. Also, a comparison between results and experimental data is performed.

1. Introduction

Volumetric loading is defined as the ratio of propellant volume to chamber inner volume. One of the goals in solid rocket motor design is to have as large volumetric loading as possible keeping the basic requirement unaffected. These basic parameters are the blocking factor, sliver area, and progressivity or neutrality parameters [1, 2]. There are various types of slots, for example, the fin slot or radial slots used in the second stages of French ballistic missiles (SEP P4.0) (figure 1) [3,4]. and in space motors like in the Indian SLV-3 Apogee (figure 2) [5] and FW-4D motor (figure 3) [6]. Other examples are the through-web axial slot, slots connecting to the inner and outer surfaces and extending to a part of the grain length as in SA-3 Goa sustainer motor [7].

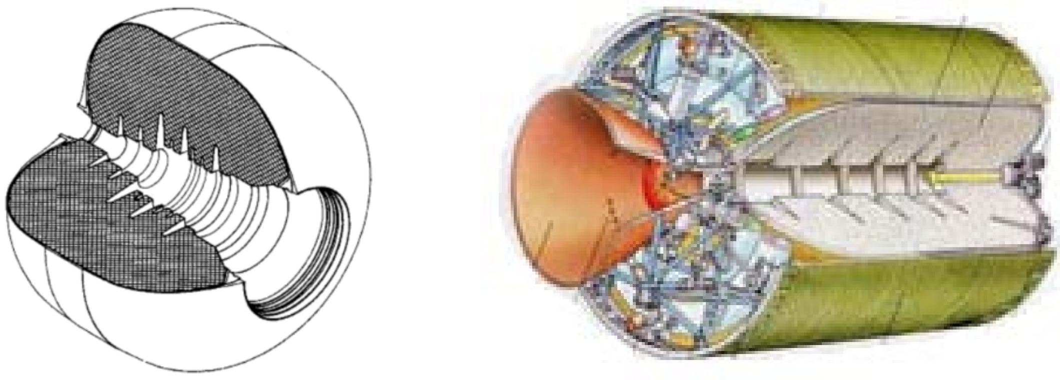

Figure 1 Second stages of French ballistic missiles (SEP P4.0) [3,4]

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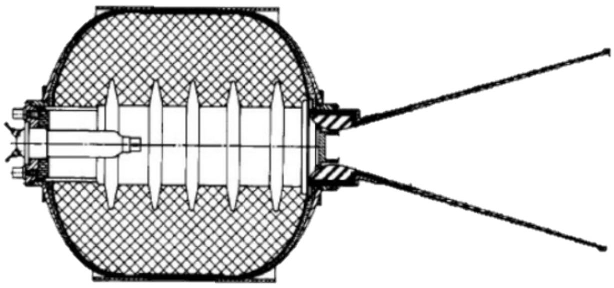

Figure 2 SLV-3 Stage 4 motor [6]

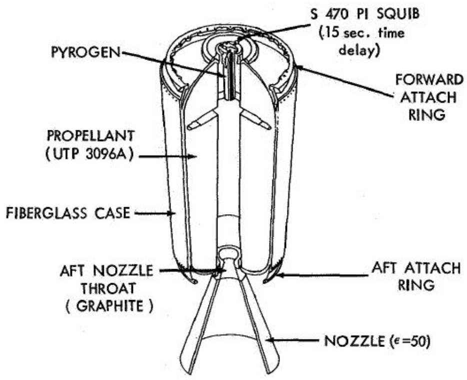

Figure 3 FW-4D Motor [7]

Through-web axial slot grain (in this research, it will be shortened as slotted grain) has the advantages of being free of sliver and free of stress-concentration regions that occur in other internal burning grains (e.g., star grain and wagon wheel grain). It has a larger volumetric loading compared to other internal-external burning grains with a disadvantage of exposing the motor wall to hot gases. Zayed [8] studied grains with through-web slots and showed that there are two important parameters: the length ratio $\lambda = \frac{L_1}{L}$, and the number of slots (figure.4)

b. 3 Slots Grain

a. 4 Slots Grain

Figure 4 Configuration of slotted grains [8]

Stone [9] derived a set of equations that describe the evolution of burning perimeter and port area at a given burn distance in terms of the design parameters shown in figure.5. Also, the slotted grains find a wide application in base-bleeding artillery projectiles [10]. It was found that increasing the number of slots, can increase the range of the base bleed artillery.

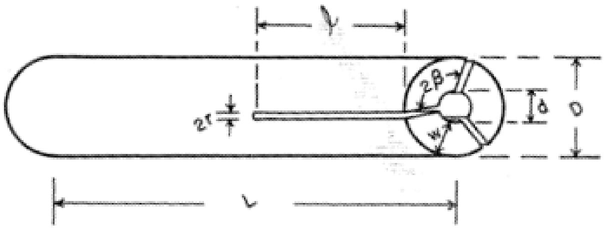

Figure 5 Slotted tube grain design [9]

2. Slotted grain: baseline case

2.1. Geometry

The baseline grain is the solid propellant grain used in the second stage of ex-USSR air-defense missile SA-3 Goa [11]. The basic dimensions of that grain are shown in figures .6 and 7. Solid propellant charge 5b29 is made as a cylindrical single-perforated grain with six radial slots near its front end face. The outer surface and the tail end face of the grain are inhibited. The grain is loaded into the engine body through its tail portion with the nozzle fairing removed; the grain is fixed in the body against axial and radial movement employing supporters.

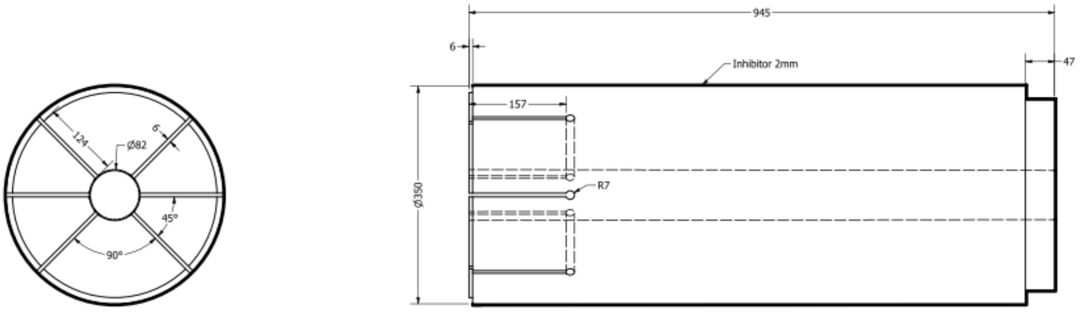

Figure 6 Grain of Sustainer of SA-3 Goa

Figure 7 3D CAD of the slotted grain of SAM-3

2.2. Grain Burnback

Due to the complexity of the analytical solution of the equations presented in [9], in this research drafting technique is utilized for studying burnback analysis of slotted grain. The drafting technique is the oldest technique used in grain burnback analysis, where the evolution of the burning surface is evaluated by combining basic shapes to describe the grain initial geometry and the burning surface is assumed to propagate normal to itself [1]. In this case, CAD software is used to propagate the initial surfaces till burnout. The main drawbacks of this method are that it is discrete, requires high human-computer interaction which may lead to errors, and it is also a time-consuming method. However, in this case, where the grain is 3D and complicated analytical analysis, the drafting technique is a good choice for the preliminary study of slotted grain. The steps of this burnback are shown in figure. 8

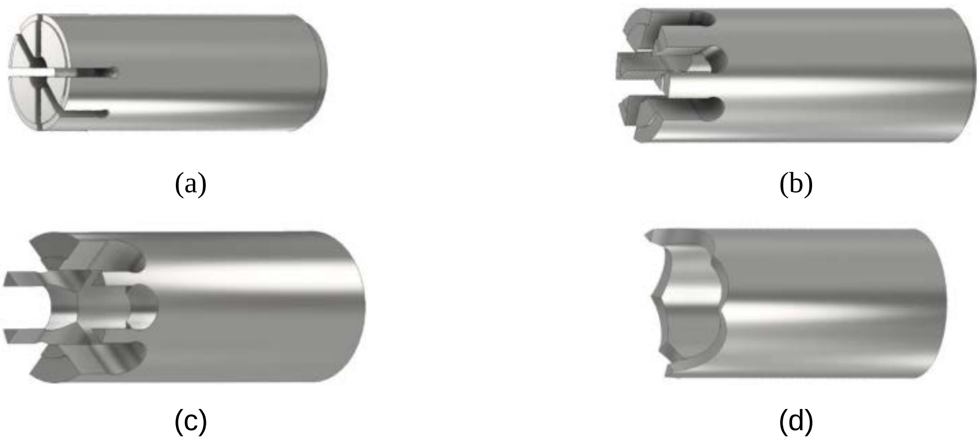

Figure 8 Burnback steps for the baseline grain

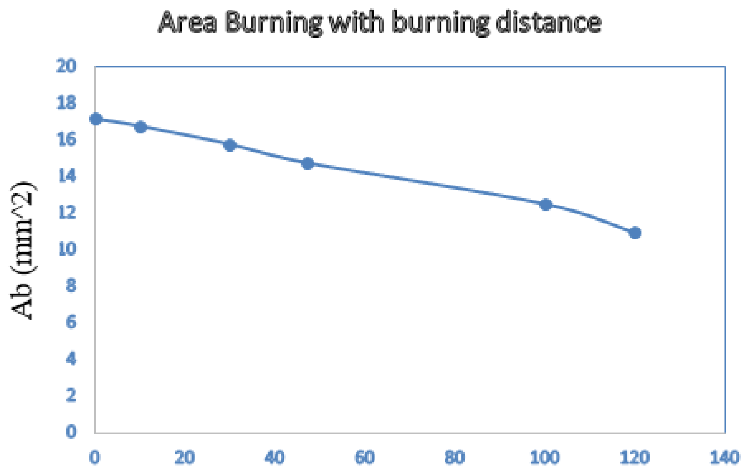

Figure 9 Burnback results for the baseline grain

The results (figure. 9) show that the baseline grain has regressive behavior which is expected as from a tactical viewpoint, the main function of the sustainer motor is to maintain the missile speed constant, with propellant depletion, it requires less thrust to keep the same velocity.

3. Experimental Validation

To predict the pressure-time curve a 0-D internal ballistic prediction module (IBPM) was applied. The basic equation for this module according to [1] is

$$V_c \frac{dP_c}{dt} = \rho_{sp} R T_c A_b a P_c{}^n - \Gamma P_c A_{cr} \sqrt{R T_c} \quad (1)$$

where V_c= chamber free volume, Pc = combustion pressure (stagnation pressure), ρ_{sp} = solid propellant density, R = gas constant, T_c = combustion temperature, A_b = burning area, and A_{cr}= nozzle critical area. Comparison between the experimental results and the analytical results for the baseline grain is shown in figure. 10, the comparison shows a good agreement with the progressive behavior captured. However, there is a deviation between the experimental and analytical with the error increase near the end of burning. This error can be attributed to uncertainties in burning rate law or nozzle erosion as discussed in a previous article for the same research group. These uncertainties can be evaluated using an optimization module [12].

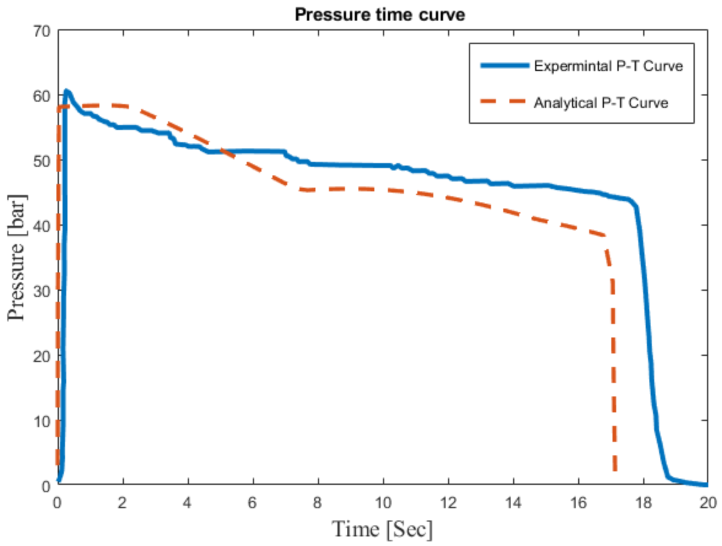

Figure 10 Pressure time curve for sustainer of SAM-3

4. Parametric study

In order to evaluate the importance of each geometric parameter, a parametric study using a single parameter at a time variation is pursued considering the basic grain as shown in figure.6, There will be three groups, each group has one variable parameter keeping all other parameters constant

- **Group A**: Effect of slot length relative to total grain length.
- **Group B**: Effect of the internal radius of grain
- **Group C**: Effect of slot width.
- **Group D**: Effect of the number of slots.

4.1 Group A: Effect of slot length relative to total grain length

In this group, the variation of percentage of slotted part is investigated, with 3 more cases other than the baseline case; the slotted length is 25%, 50%, and 75% of total grain length, with values of slotted length in table 1.

Table 1 Changes in lengths of slotted grain

$Case\ A$	$Lsg1 = 0.25\ Lg$	$Lsg2 = 0.5\ Lg$	$Lsg3 = 0.75\ Lg$
	236.25	472.5	708.75

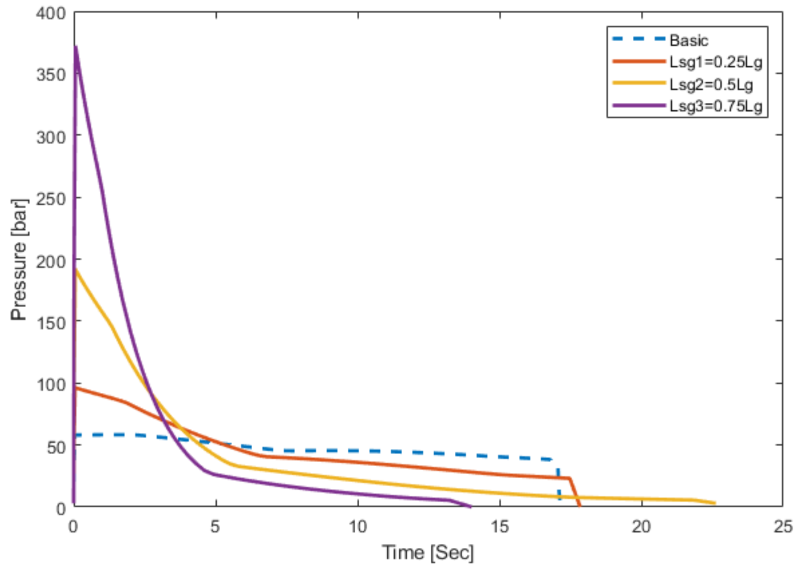

Figure 11 Pressure time curve for cases in group A

From figure.11, it is obvious that increasing the slotted length increases regressivity in the grain burnback analysis by increasing the initial burning surface and decreasing the final burning area with a shorter burning time.

4.2 Group B: Effect of the internal radius of grain

In this group, the variation of the inner radius of the grain is investigated, with 2 more cases other than the baseline case, with values of slotted length as in table 2.

Table 2 Changes in the internal radius of slotted grain

Case B	r_{in1}(mm)	r_{in2}((base radius)	r_{in3}
	25	41	60

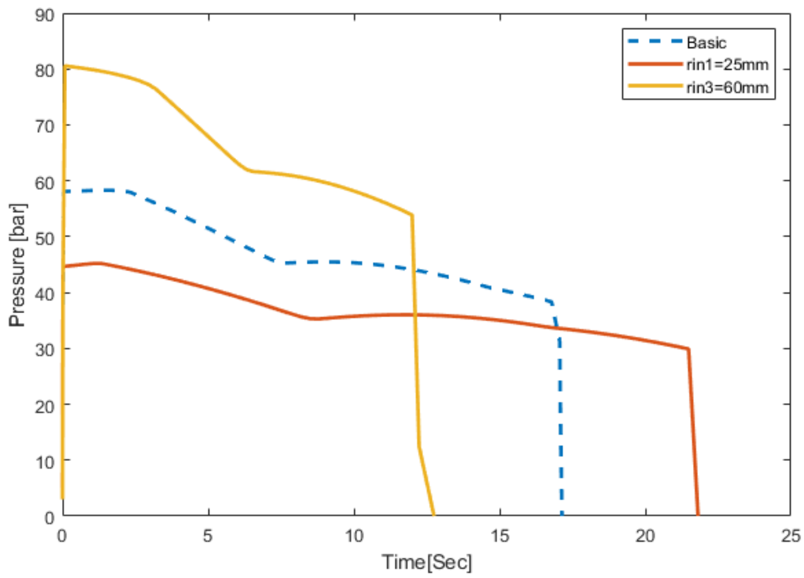

Figure 12 Pressure time curve for cases in group B

From figure.12, it is obvious that changing the inner radius does not affect the regressive behavior as both initial and final burning surfaces increase. However, increase the inner radius, increases the burning area and combustion pressure and decreases the burning time.

4.3 Group C: Effect of slot width

In this group, the variation of slot width is investigated, with 3 more cases other than the baseline case, with values of slotted length as in table 3.

Table 3 changes in the width of the slotted grain

$Case\ D$	b $(width\ of\ slots)$	$b2$	$b3$	$b4$
	3 (Basic)	4	8	10

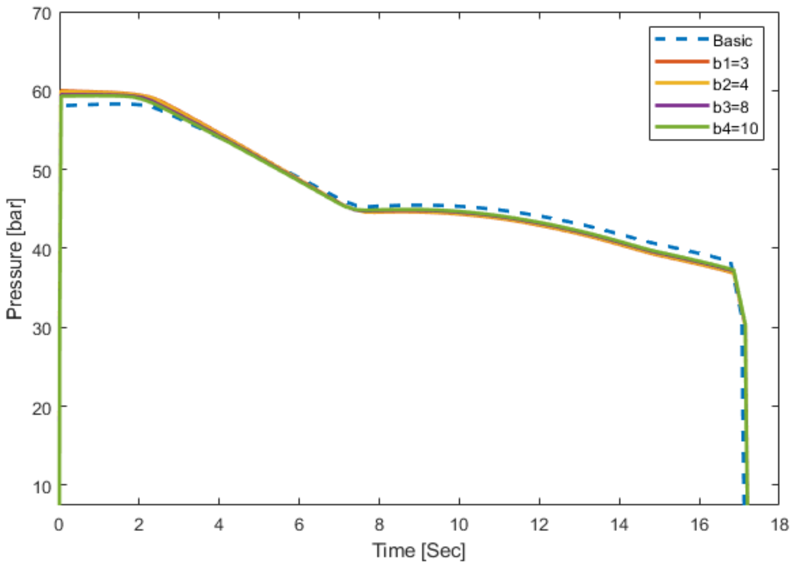

Figure 13 Pressure time curve for cases in group C

From figure.13, it is obvious that changing the slot width has a very minor effect on grain burnback.

4.4. Group D: Effect of the number of slots.

In this group, the variation of the number of slots is investigated, with 3 more cases other than the baseline case, with values of slotted length as in table 4.

Table 4 changes in the number of slotted grain

$Case\ D$	n $(number\ of\ slots)$	$n1$	$n2$	$n3$
	3 (Basic)	4	5	6

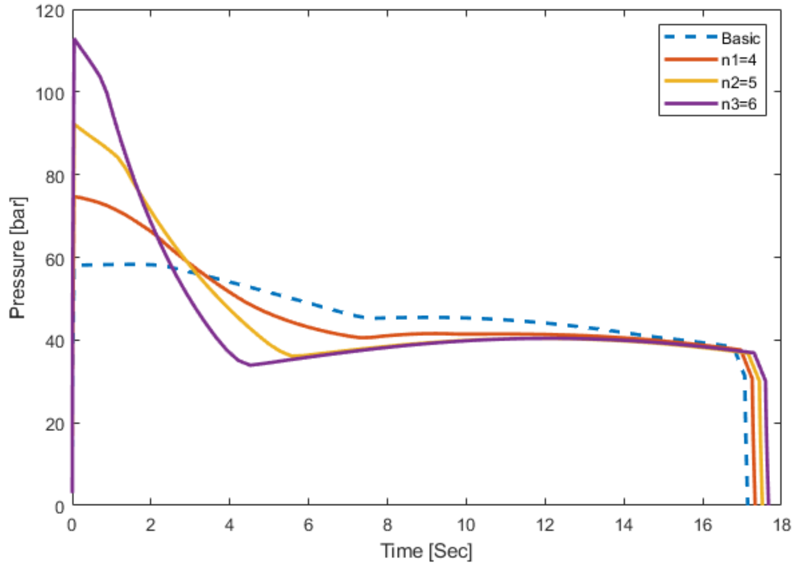

Figure 14 Pressure time curve for case D

From figure.14, it is obvious that changing the number of slots has a large effect on grain burnback, increasing the number of slots increases the regressive behavior of the grain with increased initial burning surface and decreased final burning area.

5. Conclusion and future work

Through-web axial slot grain (slotted grain) has the advantages of sliver free and no stress-concentration regions that occur in other internal burning grains as star grain and wagon wheel grain. Moreover, it has larger volumetric loading compared to other internal-external burning grains. It has the drawback of exposing the motor wall to hot gases. The drafting technique was used to study the effect of geometric parameters on the performance of slotted grain. First, the technique was validated against experimental data, then a variation of one single parameter at a time technique was applied to find the effect of each parameter. It was clear that the width of the slot has a minor effect, while slot length and number of slots have a great effect on the regressive behavior.

While regressive behavior is required for some missile applications especially in the sustainer phase, this objective may compromise other performance parameters. So, a multidisciplinary optimization module should be applied to achieve the requisite multi-objective optimization.

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